MOMENTS OF FORCE AND MECHANICAL POWER IN JOGGING

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Abstract—A sagittal plane biomechanical analysis of 11 slow jogging trials yielded joint moments of force, power curves and positive and negative work at each of the joints of the lower limb. The following can be summarized:

1. The total moment of force pattern of the lower limb was primarily extensor during stance and flexor during swing. The hip had an extensor peak at 20°, the knee at 40°, and the ankle at 60° of stance.
2. The variability of the moment patterns across all trials was considerably less than that seen during natural walking.
3. Two power bursts were seen at the ankle, absorption early in stance followed by a dominant generation peak during late push-off. The average peak of power generation was 800 W with individual maximums exceeding 1500 W.
4. Power patterns for all trials showed the knee to have five distinct phases: an initial shock absorbing peak during weight acceptance, a small generation burst during early push-off, a major absorption pattern during late push-off continuing until maximum knee flexion, a third absorption peak decelerating the leg and foot prior to impact, and a final small positive burst as the knee flexors rotate the leg posteriorly to further reduce the forward velocity of the foot prior to heel contact.
5. Power patterns at the hip were neither large nor consistent indicating the dual role of hip flexors and extensors relative to the trunk and lower limb stability.
6. Positive work done by the ankle plantarflexors averaged three times that done by the knee extensors, and in some joggers the ankle muscles generated eight times that of the knee muscles.
7. Over the entire stride the knee muscles absorbed 3.6 times as much energy as they generated; the ankle muscles generated 2.9 times as much as they absorbed.

INTRODUCTION

With the recent popularity of jogging during the past decade there is a need for a more detailed look at the biomechanics of the movement of running. Cadence, temporal, velocity and joint angle variables have been reported for treadmill and overground running (Elliott and Blanksby 1976; Bates et al., 1979; Nelson et al., 1972). Considerable work has also been reported on mechanical energy aspects of running but limited research has been done on the kinetics and the joint energetics. The kinetic and potential energies of the legs have been examined (Margaria et al., 1963; Cavagna et al., 1971; Cavagna et al., 1976) but such studies have been criticized on the basis that the point mass model they assume neglects the large energies (translational and rotational kinetic) associated with the reciprocal movements of the legs and arms. Also, in some cases (Fenn, 1930; Cavagna et al., 1976; Norman et al., 1976; Cavagna and Kaneko, 1977) the absolute changes in kinetic and potential components were added in such a way as to deny the fact that energy exchanges were taking place within each segment, or between adjacent segments. Furthermore, even a correctly calculated total body energy curve (Ralston and Lukin, 1969; Winter et al., 1976a; Zarrugh, 1981) yields no information as to the source of generation and absorption of that energy. Only by examining the mechanical powers at each joint can an assessment of the importance of the muscles at the ankle, knee and hip be ascertained. Elftman (1939a, b) in his classic studies presented methods for calculating the rate of change of energy of the legs, the rate of energy transfer across the joint centres, and the rate of work done (positively and negatively) on the leg. Elftman (1940) extended this work to analyze one stride of one runner. Morrison (1970) calculated the total energy generation and absorption at the knee during walking. Cappozzo et al. (1976) calculated the positive and negative work done at the ankle, knee and hip at intervals over the stride period. Quanbury et al. (1975), Winter et al. (1976b) and Robertson and Winter (1980) extended these studies to calculate the work/energy balance in the foot, leg and thigh, and also calculate the rate of energy generation, absorption and transfer at the ankle, knee, and hip during the walking stride. Quite recently a kinetic analysis of fifteen sprinting trials (Mann, 1981) revealed basic patterns of moments at the ankle, knee and hip.

The purpose of this study is twofold. The first aim is to report the patterns of moments of force at the ankle, knee and hip for a group of adult joggers and to determine if the net extensor pattern at all three joints, called the support moment (Winter, 1980), is quite consistent across all subjects and to compare the variability of these patterns with that seen in walking. Secondly, an analysis of the patterns of mechanical

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power generation and absorption at each of the joints is reported, aimed at determining the major function of each muscle group in terms of positive and negative work.

METHODOLOGY

A total of 11 normal adult subjects were analyzed in the Gait Laboratory in the Department of Kinesiology at the University of Waterloo. The subjects' ages ranged from 20 to 49 yr, the mean height was 176 cm ($\sigma = \pm 1$ cm) and their mean mass was 72.4 kg ($\sigma = \pm 4.2$ kg). Each subject wore his or her own running shoes and had reflective markers placed on the following anatomical landmarks: toe, 5th metatarsal joint, heel, ankle (lateral malleolus), lateral epicondyle of femur, greater trochanter, iliac crest, and mid-trunk region. Each subject was instructed to jog at a slow speed while running on a slightly raised walkway (30 cm high) while a tracking cart containing a TV and cine camera (50 frames/s) was guided on a track beside the walkway at a distance of 4 m. Background markers on the wall beside the walkway gave a reference so that the body coordinates could be properly scaled, and obtained as absolute coordinates in a similar manner as was developed for television analysis of gait (Winter et al., 1972). Simultaneously, force plate data were recorded along with a 50-Hz synchronizing pulse obtained from the cine camera. The force plate data yielded the vertical and fore-aft shear ground reaction forces, and when combined with the cine data the centre of pressure of this force vector under the foot was obtained.

Coordinates of the body and background markers were extracted from the cine film using a Numonics Digitizer interfaced with a Sorcerer Microprocessor. Raw coordinate data were scaled, then corrected for parallax error between the plane of progression of the jogger and the plane of the background reference markers. Using the background markers as a spatial reference the limb marker absolute coordinates were calculated and then transferred to an IBM 370 computer for kinematic processing. The 'noise' in this coordinate data, mainly due to the digitizing process, has been calculated to have an RMS error of 2 mm or less for all markers. Prior to link segment modelling the coordinates were digitally filtered (Winter et al., 1974) using a 4th order zero lag low pass Butterworth filter cutting off at 8 Hz. Validation for the filtering using a cut-off at the 6th harmonic (in this case about 8 Hz) and finite difference calculation of velocities and accelerations is supported by the study by Pezzack et al. (1977) and by a subsequent study (Winter and Wells, 1978b) that included cadences from slow walking to slow jogging. For each subject the anthropometric constants were obtained using tables provided by Dempster (1955) based on the subject's height and mass.

A standard link segment kinetic program (Bresler and Frankel, 1950) was used to calculate the vertical and horizontal forces plus net joint moments at the ankle, knee and hip for one complete stride commencing with heel contact on the force plate. The net support moment, $M_s$, which is the algebraic sum of the moments at the ankle, knee and hip (with extensor moments being positive), was calculated (Winter, 1980). It should be noted that the foot segment was modelled assuming a rigid segment between the ankle and the 5th metatarsal marker, the toe marker was not used for analysis because of the flexion and extension of the m–p joints, especially during late push-off and early swing.

The power at each joint was calculated using the formula

$$P_j = M_j \cdot \omega_j \quad \text{W} \quad (1)$$

where $M_j$ is the net moment of force at joint $j$ and $\omega_j$ is the joint angular velocity.

The convention of $M_j$ and $\omega_j$ is such that $P_j$ was positive if $M_j$ and $\omega_j$ are of the same polarity, i.e. a concentric contraction. Conversely, for eccentric contractions $P_j$ was negative. The area under the resultant power curves at each joint gave the positive or negative work done (in J) for each phase of activity of muscles at each joint. Because the joint velocity was used instead of the absolute angular velocity of each segment information concerning energy transfers between adjacent segments was not available (Robertson and Winter, 1980).

RESULTS

Joint and support moment of force patterns

The ankle, knee and hip moments for one of the subjects is plotted in Fig. 1, with extensor moments shown as being positive, flexor as negative. The sum of these three moments, the support moment, $M_s$, is also shown (Winter, 1980).

In order to determine the average moment of force patterns for the eleven subjects the same normalization procedure was used as reported previously (Winter, 1980). The stance period was set at 100% and the maximum $M_j$ for each runner was set at 100% Swing period was calculated to average close to 130% of stance, thus the swing period for all joggers was normalized to 130% of stance. The ensemble averages of the support, hip, knee and ankle moments are presented in Figs 2, 3, 4 and 5 respectively. The vertical bars indicate one standard deviation at each of the averaging intervals. The coefficient of variation for each of the moment averages was calculated as $\sigma M_j / |M_j| \times 100\%$, and is reported on each curve. A summary of these five moment of force patterns is presented in Fig. 6.

Joint power and work

For purposes of documentation the detailed curves for each subject will not be presented; rather an example calculation of power and work for one jogger...
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Fig. 1. Moments of force calculated during a running stride for one of the subjects during a slow jog. Support moment, \( M_s \), is the sum of all three joint moments, with positive polarity for extensor, negative for flexor. \( M_f \) shows a net extensor pattern for \( 90\% \) of stance.

Fig. 2. Ensemble average of 11 jogging trials of support moment. Time axis was normalized for all trials, so that swing was \( 130^\circ \) of stance, and \( Y \) axis was normalized to maximum \( M_s \) for each trial set to \( 100^\circ \). Vertical bars represent \( \pm 1 \) standard deviation from the mean at each point in time. Coefficient of variation was calculated separately for stance and stride periods.

Fig. 3. Ensemble average of 11 jogging trials of the ankle moment. Normalization procedure was same as described for Fig. 2.

Fig. 4. Ensemble average of 11 jogging trials of knee moment. Normalization procedure was same as described for Fig. 2.

Fig. 5. Ensemble average of 11 jogging trials of hip moment. Normalization procedure was same as described for Fig. 2.

is presented. For subject WN20P (Fig. 7) the knee angle plot shows the phases when the knee is flexing or extending, the moment curve has extensor moments as positive and the power curve is the product of the knee moment and angular velocity. The area under each phase of the power curve is the work done at the knee joint and is shown in J. Similar comments apply to Fig. 8 which shows identical calculations for the ankle joint. A summary of the three powers, calculated at each joint is shown in Fig. 9. along with the major phases of power generation and absorption labelled. In all subjects there were two major phases seen at the ankle (labelled A1 and A2), and five major power
Fig. 6. Summary of moments of force patterns at the ankle, knee and hip for 11 trials. See text for detailed discussion of functional significance.

Fig. 7. Plot of joint angle, moment of force and power at the ankle for one of the subject trials. The subject’s mass is 79 kg, cadence 162 and velocity 2.72 m/s. Two major power bursts are evident: negative power (A1) as plantarflexors slow down the leg as it rotates over the flat foot; positive power (A2) as the foot plantarflexes to generate the major burst of mechanical energy.

Fig. 8. Plot of knee angle, moment of force and power. Five power phases are evident: K1, energy absorption by knee extensors; K2, positive work as extensors shorten under tension; K3, deceleration of leg and foot as thigh drives forward during late stance and early swing; K4, deceleration of swinging leg and foot by knee flexors prior to heel contact; and K5 a small positive burst to flex the leg slightly and slow down its forward motion prior to heel contact.

Fig. 9. Composite of power/work patterns at all three joints. Major generation of energy is done at the ankle, with a minor contribution at the knee. Power levels at the hip are small, and when compared with other trials no pattern was evident.
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The power bursts at the hip were neither large nor consistent in their pattern, thus no label was given. Table 1 summarizes the work done during each of these phases for the 11 trials.

### DISCUSSION

The individual moment of force patterns as presented in Figs 2–5, and summarized in Fig. 6 shows how the runners responded to the forces acting during stance and generated the required forces during swing. Initial comments should be made about the rather small variability in these moment patterns compared with the considerable variability reported in these same patterns during normal walking (Winter, 1980). The coefficient of variation is lowest for the ankle (stance—36.2%, stride—37.2%), and increases for the knee (stance—45.3%, stride—45.8%) and is highest for the hip (stance—77.5%, stride—86.8%). Comparative coefficients of variation during stance for 17 subjects walking at their natural cadence are: ankle—51%, knee—186%, and hip—153%, and for 11 subjects walking at a fast cadence are: ankle—37%, knee—81%, and hip—62%. Walking at one's natural cadence not only is accomplished without any conscious effort but also is well within the extremes of forces possible at each joint. Thus compensating patterns at individual joints would be at a very low level and would occur at the subconscious level. Fast walking and slow jogging, on the other hand, represent a movement towards the higher level of forces and are achieved as a result of a conscious over-ride of the rather loose patterns required for natural walking. Thus the neural control pattern appears to become less variable, especially as seen at the knee and hip where major biarticular muscles act.

Figure 6 summarizes the flexor/extensor patterns during the stance and swing phases of the running stride. The support moment showed a primarily extensor pattern during stance, flexor during the first half of swing and extension during late swing. It is interesting to note the relative timing of the extensor peaks at the three joints. The hip peaks at 20% stance, the knee at 40% stance and the ankle near 60% stance. The hip moment reverses before mid-stance and remains flexor until mid-swing; this flexor moment decelerates the backward rotating thigh and reverses the thigh’s direction to drive it forward into swing. The moderate extensor moment at the end of swing serves to decelerate the thigh to prepare for the next heel contact. It is interesting to note the shape and polarity of this hip moment compared with the knee moment at the same time. The hip has an extensor moment with a peak of about 30 N.m and is 180° out of phase with the flexor moment at the knee which has a peak of about 15 N.m. When one considers the mechanical advantage of the hamstrings at the hip to be about twice that at the knee these curves provide overwhelming phases at the knee (labelled K1, K2, K3, K4 and K5).
circumstantial evidence of the dual role of the hamstring muscles during this phase of swing. Mann (1981) has noted similar patterns in sprinters.

The functional significance of the knee and ankle moment patterns in terms of energy generation and absorption can best be understood by examining the power and work analyses. Figure 7 shows the time plots of ankle angle, moment of force, and power for one of the jogging trials (WN20P). Very shortly after heel contact (HC) the foot was flat on the ground and the leg rotated over it, i.e. ankle dorsiflexing. During this time a large plantarflexor moment developed, and as these muscles lengthened under tension they absorbed 26J of mechanical energy (power phase A1). About mid-stance the ankle started to plantarflex, and as these muscles shortened the dominant generation of energy took place. The power peak during this phase (A2) was about 700 W and the positive work done was 56J. At toe-off (TO) and throughout the entire swing period the ankle moment was very low, with sufficient dorsiflexion to ensure that the foot clears the ground during swing.

Figure 8 is a similar plot for the knee joint. Five power phases were seen in all joggers; here they are labelled K1, K2, K3, K4 and K5. Immediately after heel contact until mid-stance the knee flexed under the influence of weight bearing. Flexion was arrested, mainly due to the rapid rise in knee extensor moment; the lengthening of these extensors resulted in a peak negative power of nearly 600 W (K1) with a corresponding energy absorption of 53J. From mid-stance until late push-off the knee reversed direction and during this shortening of the quadriceps muscles 31J of positive work was done (K2). During phase K3 the knee was flexing but the extensor muscles were still active. This extensor moment served to decelerate the shank and foot as they rotated in a posterior direction during early swing. The power required to do this is not large (70 W) but the energy absorbed is not insignificant (11J). Power peak K4 resulted from absorption of energy by the knee flexors as the leg and foot are decelerated during the reach phase of swing. The negative work associated with this energy absorption is also not insignificant (24J). Finally, about 60 ms before heel contact the knee flexors actually reversed the direction of the knee joint and a small concentric contraction (phase K5) slowed down the foot and leg. An examination of the kinematics of the heel marker reveals for these joggers that the forward velocity averaged 2.77 m/s at the start of K5 and was reduced to 0.63 m/s immediately prior to heel contact. The duration of K5 varied from 40 to 90 ms. On the average just under 4J work was done and this work does not aid in the forward progression but appears to be a necessary overhead to reduce the forward velocity of the foot prior to contact.

Figure 9 is a composite of the power/work curves at all three joints for this same jogging trial. The relative importance of the positive and negative work done at each of the joints is demonstrated. The hip had relatively low power levels, and when different trials are compared no consistent patterns are seen. The major conclusion that results from this lack of pattern appears to be due to the dual role of the hip flexors and extensors during running. They are obviously involved with the lower limb in supporting it early in stance and initiating its forward drive prior to swing. However, these muscles are also responsible for maintaining a stable upper body, and it is probably fine adjustments of the trunk that increased the variability that masked major patterns that might otherwise be evident. It is also worth noting that the knee extensors do not contribute any energy to the swinging leg and foot. It was anticipated from the extensor pattern of the knee muscles early in swing that they might be responsible for a positive power phase between K3 and K4. However, in all trials by the time the knee began to extend (about 30% of swing period) the momentum of force had reversed to a flexor pattern as the knee flexors began absorbing energy from the swinging leg.

The relative importance of the knee and ankle muscles as absorbers and generators of mechanical energy are demonstrated in Fig. 9. The ankle is primarily an energy generator, the knee an absorber, and the power levels at the ankle are quite high. Table 1 is a summary of the power/work bursts at the ankle and knee for all trials. The average peak positive power at the ankle (A2) is over 800 W with some peaks as high as 1500 W. This can be compared with 150 W for slow walking and 500 W for fast walking (Winter and Robertson, 1978a). The knee on the other hand had average peak powers of 273 W (K2). In terms of relative importance as a generator of new energy the ankle does three times the work of the knee (59.0 vs 19.6 J). The knee muscles over the entire stride absorbed 3.5 times as much energy as they generated (69.2 vs 19.6 J), and the ankle was dominant as an energy generator (59.0 vs 22.2 J). Such findings are important in the training protocol of joggers and in the rehabilitation of the injured runner. About 75% of the chronic injuries resulting from jogging (tendonitis, shin splints, stress fractures, plantar fasciitis and chondromalacia) appear to be related to the high forces and powers that occur at push-off when the knee is flexing and the ankle is plantarflexing. Most current training on 'machines' involves concentric exercises of the knee extensors, but these findings point to the need for eccentric knee exercise and concentric plantarflexor training.

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REFERENCES


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